The LBNE Scientific Capability Review

Dec. 18th, 2011

This document summarizes the Scientific Capability Review Process and consists of four sections:

1) Committee Charge.
2) Committee Report.
3) Questions and Responses from/to the committee. Responses produced by the LBNE Physics Working Group.
4) Review Agenda.

   In an accompanying document we have documented actions on the points raised by the committee report. These were produced by the collaboration spokespeople and the Physics Working Group leader.

We would like to express our thanks to the committee in helping us to improve our evaluation of detector options for LBNE.

Robert Svoboda (co-spokesperson), Milind Diwan (co-spokesperson), Robert Wilson (Physics Working Group leader), Maury Goodman (deputy-spokesperson).

Section 1: Description of the Review Process

Charge to the Committee:

Purpose: The Long Baseline Neutrino Experiment (LBNE) is considering two options for an initial far detector configuration at the Homestake site in South Dakota. These are:

- A liquid argon detector located at either the 800 or 4850 level
- A water Cherenkov detector located at the 4850 level

Cost considerations allow only one of these options to be built in the first stage, which will utilize a 700 kW beam from Fermilab and the large underground space at Homestake to conduct a broad scientific program in neutrino physics, grand unification, and astrophysics[1].

The LBNE Science Collaboration and Project Management have decided to make the choice of which configuration to use before the end of 2011, as this will facilitate concentrating on a single major option, thus advancing the schedule significantly and lowering project costs in this early stage. The principles and procedures to be followed in making this decision are covered in the documents “Far Detector Technology Choice General Principles[2]” and “Procedures for LBNE Far Detector Configuration Decision[3]”. A key element in the decision process is a review by an external independent committee of the scientific capabilities of the two far detector options. The review will be charged by and report to the LBNE Collaboration Co-Spokespersons. This is the charge to that review committee.

The LBNE Collaboration has prepared Case Study[4] proposals that describe the scientific potential and program that would be followed for both scenarios and a Conceptual Design Report[5] (CDR) that describe the technical design of the LBNE Project, including the designs of the proposed liquid argon and water detectors. These documents will form the basis for the far detector configuration choice, and are key input to the Scientific Capabilities Review.

Charge: The Scientific Capabilities Review Committee is asked to evaluate and compare each of the two approaches to building LBNE with respect to its capabilities to achieve the science goals of the experiment[1]. The Committee’s review should consider, but not necessarily be limited to, the following questions:

1) What are the crucial assumptions made by proponents in deriving the sensitivity for fulfilment of the science goals?
2) How well are these assumptions justified by the proponents based on extrapolation from existing experiments, test beam measurements, and/or validated simulations?
3) How well have the proponents considered consequences of detector performance being degraded from the assumptions by “reasonable” variations, where “reasonable” is determined from experience with similar detectors?
4) Are there major scientific risks and opportunities that are not covered sufficiently in the Case Studies?

Procedure and Timescale for the Review: The committee is asked to review the documentation provided by the Science Collaboration and then to meet with proponents of the two scenarios in order to hear presentations and discuss in depth with collaboration members issues relevant to the charge. Tentatively, this in person review will be scheduled in the time frame of early November at Fermilab, starting at 9am the first day and ending at 1:30pm the last day. The first two days would consist mostly of public presentations plus question and answer sessions, while the last half-day would consist of a closed executive session.

Final Report: A final report to the Spokespersons is requested by the November 18. The report should be a public one, and an oral presentation to the LBNE Executive Committee (possibly via phone) is requested upon completion.

[1] Physics Research Goals of the LBNE Project, LBNE-doc-3056, 18 Nov 2010, http://lbne2-docdb.fnal.gov/0030/003056/003/KeyAssumptions-PhysicsGoals_V1.0.pdf.

[2] Far Detector Technology Decision General Principles. LBNE-doc-4099, 28 July 2011, http://lbne2-docdb.fnal.gov /0040/004099/002/Far%20Detector%20Technology%20Decision%20General%20Principles%20-%20Approved.pdf.

[3] Procedures for LBNE Far Detector Configuration Decision. LBNE-doc-4099, 28 July 2011, http://lbne2-docdb.fnal.gov /0040/004099/002/Far%20Detector%20Technology%20Decision%20General%20Principles%20-%20Approved.pdf.

[4] LBNE Case Study Report: 200 kt Water Cherenkov Far Detector, LBNE-doc-3495, http://lbne2-docdb.fnal.gov:8080/0034/003495/007/case_study_v3.1.pdf; LBNE Case Study Report: Liquid Argon TPC Far Detector, LBNE-doc-3600, http://lbne2-docdb.fnal.gov:8080/0036/003600/002/lar_casestudy_v1.1.pdf.

[5] LBNE Conceptual Design Report, LBNE-doc-2339, http://lbne2-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=2339.

Committee Members:

Prof. Paul Grannis, SUNY Stony Brook
Dr. Dan Green, Fermi National Accelerator Laboratory
Prof. Koichiro Nishikawa, Institute of Particle and Nuclear Studies, KEK

Prof. Hamish Robertson, University of Washington

Prof. Bernard Sadoulet, University of California Berkeley

Prof. Dave Wark (Chair), Rutherford Appleton Laboratory/Imperial College London

Process:

1) Review of written materials and initial list of questions and comments.
2) Response of the collaboration to questions and comments on the written materials
3) Oral presentations
4) Written report from the committee
5) Response to the points in the written report

SECTION 2: **Report from the committee.**

Report of the LBNE Scientific Capability Review Committee

Dec. 14^{th}, 2011

1 Introduction

This document reports the views of the LBNE Scientific Capability Review Committee after its consideration of the goals, potential capabilities, and risks of the two proposed technologies for the far detector for the LBNE experiment. The committee was convened by the collaboration to give advice on a realistic estimate of relative scientific capability of each technology, and where we felt the key risks lay. The committee consisted of:

Prof. Paul Grannis, SUNY Stony Brook
Dr. Dan Green, Fermi National Accelerator Laboratory
Prof. Koichiro Nishikawa, Institute of Particle and Nuclear Studies, KEK
Prof. Hamish Robertson, University of Washington
Prof. Bernard Sadoulet, University of California Berkeley
Prof. Dave Wark (Chair), Rutherford Appleton Laboratory/Imperial College London

The committee worked largely from material provided by the proponents of each different technology within the LBNE collaboration, however we also consulted material produced by other collaborations around the world and used our own experience of designing and building large particle physics experiments. The committee was charged specifically with considering the scientific capabilities and risks. We were not asked to review costs, schedules, or technical risks, however it is at some level impossible to consider scientific risks without considering these other risks. The findings and recommendations below therefore include some considerations of technical, cost and schedule risks, but only where those are directly tied to the scientific capabilities. While we were only charged with considering the goals of LBNE itself, the scale of the facilities for this effort and its critical impact on the future Fermilab programme make it impossible to ignore the importance to the future US and world HEP programme. The Committee came to the unanimous opinion which is given below.

2 Main Physics Goals and Resulting Detector Requirements.

We list here our views on the main physics goals of the LBNE experiment and what we feel are the key resulting detector requirements that must be satisfied by either technology. Once again we concentrate on the high-level science. Obviously any detector must be reliable, affordable, and the associated technical risks should be reasonable, but those requirements will for the most part be covered by other reviews.

2.1 Long Baseline Neutrino Oscillation Physics

Long baseline neutrino oscillations are the main target of the LBNE experiment (hence the name). Neutrino oscillations were the first unambiguous particle physics demonstrated to exist beyond the Standard Model of particle physics (and so far the only, as effects such as Dark Matter and Dark Energy cannot yet be experimentally shown to arise from particle physics). The study of neutrino oscillations is of great interest to theoretical physics, as the very smallness of neutrino masses may probe physics at energy scales far beyond anything that could be seen in a terrestrial accelerator. In addition neutrino oscillations may offer one of the few experimental handles on one of the most consequential scientific questions that there is – the physics that could explain why there is more matter than anti-matter in the universe, and hence how the universe could include us.

Neutrino oscillations can be (in their simplest form) described by a mixing matrix with four parameters – three mixing angles and a CP-violating phase δ which, if non-zero, would cause the oscillations to be different for neutrinos and anti-neutrinos. The oscillations also depend on three neutrino masses, so in principle there are 7 parameters to be measured. In reality oscillation measurements yield the differences in the squares of the masses, while other direct mass measurements yield various different weighted sums of the masses. Neutrino oscillations can be modified by interactions between the neutrinos and any matter they travel through, and these matter effects are crucial in determining neutrino masses as they give information about the sign of the mass differences (oscillations in vacuum give only the magnitude of the mass-squared differences, not their signs). In practice, rather than three masses we have to measure 5 parameters – two independent mass-squared differences, their signs, and the absolute mass scale. The last of these parameters cannot be measured in oscillation experiments, so we have 8 parameters in total to measure (3 angles, one phase, 2 mass-squared differences, and two signs of the mass squared differences). Of these we have to date measured five. We know two angles (θ_{12} and θ_{23}), two mass-squared differences (Δm^2_{12}, Δm^2_{23}), and the sign of Δm^2_{12}.

The value of the third angle, θ_{13}, holds the key to the physics programme of LBNE, but luckily there is a no-lose theorem on that angle. Within the past 6 months a number of experiments including the T2K experiment in Japan, MINOS, and the reactor oscillation experiment Double Chooz have released results which point to a relatively large value for θ_{13}. The T2K result by itself disfavours $\theta_{13} = 0$ at the 99% confidence level, and all these results (when combined with existing experiments) disfavour $\theta_{13} = 0$ at over 3σ. If subsequent measurements confirm these indications, it would mean that LBNE would be able to make more accurate measurements of θ_{13} but (even more importantly) would be able to see electron neutrino appearance that would allow it to determine the unmeasured sign of Δm^2_{13} (which goes under the name of determining the mass hierarchy) and have world-leading sensitivity to the CP-violating phase δ. If, on the other hand, the current indications of $\theta_{13} \neq 0$ are not confirmed by subsequent measurements, LBNE would have sensitivity beyond any existing experiment to probe yet smaller values of θ_{13}. In addition, existing experiments (T2K, NOvA, and the 3 reactor experiments Double Chooz, Daya Bay, and RENO), when combined, will have some sensitivity to δ. However there is a no-lose theorem there as well. If the existing experiments see evidence for $\delta \neq 0$, it would only be at marginal significance (certainly less than 5σ), and LBNE would be needed to make these indications into an unambiguous discovery. If, on the other hand, existing experiments see no indications of $\delta \neq 0$, then LBNE would have the sensitivity to extend the search to smaller values. This makes LBNE an extremely important experiment for the future of particle physics no matter what the values are of the unknown parameters.

In order to measure the oscillation parameters, LBNE must perform two measurements on a beam of ν_μ produced by a new beam line at Fermilab. First, the energy spectrum of un-oscillated ν_μ must be reconstructed to measure θ_{23} and Δm^2_{23}. The value of θ_{23} is particularly interesting, because existing measurements give a value which is consistent with maximal mixing, which would point to some underlying symmetry at higher energies which we would like to understand. The key measurement, however, is to measure the energy spectrum of ν_e which appear in oscillations determined by θ_{13} and affected by the other unknown parameters. No detector, of course, directly measures the energy of a neutrino. Neutrinos interact with the matter in the detectors, producing charged and neutral particles, and the energy of the neutrino must be reconstructed from measurements of those particles. Unfortunately, in the energy range of interest for LBNE, quasi-elastic (QE) interactions, where the energy of the neutrino is most simply related to the observed properties of the charged particles, constitute a small fraction of the total, and that fraction falls with neutrino energy. Measuring a neutrino energy spectrum therefore requires disentangling the few events where the neutrino energies are well reconstructed out of a larger background from other interactions. This requires a detector with a high effective granularity, which is why the Water Cerenkov (WC), where an observed photoelectron in a phototube arises from about a millimetre of charged-particle track, and Liquid Argon tracking calorimeters (LAr) capable of seeing all particles from an interaction, are the only detectors still under consideration for LBNE.

For the crucial ν_e appearance measurement there is the additional difficulty of selecting the rare events which actually arise from ν_e interactions from the more numerous events arising from interactions from the rest of the beam. A particularly dangerous category of backgrounds arises from the production of π^0s, which decay to two photons. If one of those photons is missed by the detector the resulting single-photon looks like an electron, and hence these events constitute a major background to the single electrons expected from ν_e QE events. Another significant background is that arising from intrinsic ν_e contamination of the beam. These ν_e are part of the beam when it is created, and do not arise from oscillations, and are therefore insensitive to oscillation parameters and only get in the way. These produce a background that can only be subtracted by measuring the intrinsic ν_e contamination in a near detector at the Fermilab site and subtracting the resulting contribution from the measured event spectrum at the far detector. Doing this requires a good understanding of the relative responses of the near and far detectors, which should influence the selection of technologies for both.

All these issues can be better understood by looking at the figure, which reproduces Figure 5-3 from the LAr Case Study document supplied by the collaboration, and Figure 6-1 from the WC Case Study (the caption is taken from the latter figure, but the description applies to both).

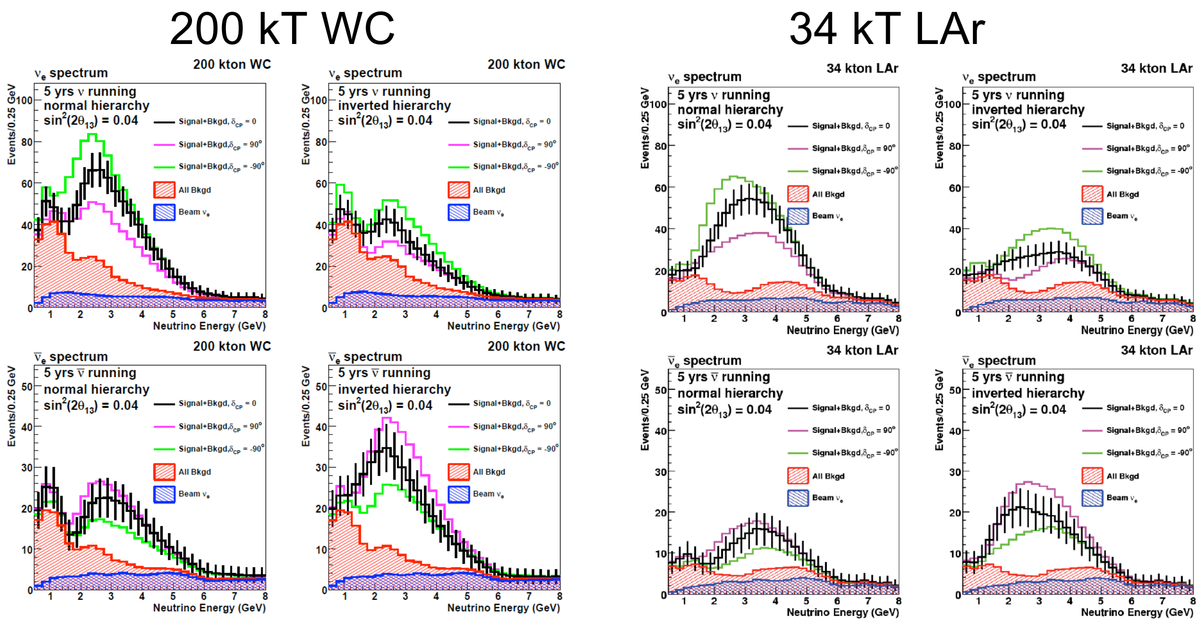

Figure 6–1: The expected ν_e spectra in a 200 kton WC detector assuming $\sin^2 2\theta_{13} = 0.04$ and 5 years of neutrino (top) and antineutrino (bottom) running in a 700 kW beam for normal (left) and inverted (right) mass hierarchies. The black points assume $\delta_{CP} = 0$ while the pink and green lines are for $\delta_{CP} = \pm 90^0$. The different background contributions are indicated by the hatched histograms with intrinsic ν_e events shown in blue and the total background contribution including intrinsic ν_e, NC, and mis-identified ν_μ CC events in red. In the case of antineutrino running, the signal and background distributions explicitly include an additional contribution from neutrinos in the beam. Error bars are statistics only.

The plots show the expected reconstructed ν_e spectra for various assumptions. The four plots on the left are for a WC detector, those on the right for a LAr. The upper four plots are for neutrinos, the bottom four for anti-neutrinos. Columns one and three are for the normal hierarchy, two and four for the inverted hierarchy (the difference being the unknown sign of Δm^2_{23}). In reality you get one column from the experiment depending on the selected technology and the true value of hierarchy. The solid histograms arise from backgrounds, and therefore must be subtracted, and the three remaining histograms in each figure show the effects of varying δ, and are hence the thing we wish to measure. A number of implications for detector design can be inferred from these plots:

- The statistics shown assume a total of ten years of running and are clearly not ideal, particularly in the second appearance maximum (the peak below 1 GeV). This puts a premium on detector mass × reconstruction efficiency × beam power.

- Because of the lack of statistics and large backgrounds at the second oscillation maximum the sensitivity to δ mostly arises from measuring the shape of the spectrum around the first oscillation maximum and how it changes from neutrino to anti-neutrino running. This makes the understanding of the size and shape of the backgrounds critical. Note that the backgrounds can be very different for neutrinos and anti-neutrinos.
- The backgrounds shown in pink arise from a wide variety of different neutrino interactions and arise primarily from detector mis-reconstructions, so that detailed understanding of the detector properties and the relative contributions of these different interactions will have an important effect on the correct interpretation of the data. The level of necessary understanding increases as the background to signal level increases, and the background is clearly larger at low energies in the WC detector than in the LAr.
- The sensitivity to the mass hierarchy comes largely from the difference in rates between neutrinos and anti-neutrinos, and from the spectral shape in the vicinity of the minimum between first and second maxima.
- The background from intrinsic contamination of the beam (shown in blue) can in principle be measured in the near detector. However this requires a detailed understanding of the differences in response between the near and far detectors.

The mis-reconstruction background is not flat, and hence must be well modelled to avoid distorting the reconstructed spectrum and hence producing a false CP signal (or hiding a real one). In our view the neutrino program has the highest physics priority within the possible capabilities of the experiment.

2.2 Proton Decay

The instability of the proton is a generic prediction of models of physics beyond the Standard Model. Observation of proton decay would be a direct observation of the effects of some higher unified theory that connects quarks and leptons, and would thus be one of the most significant particle physics measurements to be made in many years. Unfortunately, while most models agree that the proton should not be stable, there are few solid predictions for the lifetime and the preferred decay mode is also model dependent, so we are left without strong theoretical guidance on where to look. Experiments therefore try to measure as many modes as possible. Sensitivities are normally discussed for two "typical" modes, the classic mode for a WC detector $p \rightarrow e^+ + \pi^0$, and the SUSY-favoured mode $p \rightarrow K^+ + \nu$. The former is well matched to the performance of a WC detector, and therefore stringent limits ($t_{1/2} > 1.2 \times 10^{34}$ years at 90% c.l.) already exist from the Super Kamiokande experiment. This number almost rules out a 5σ discovery of this mode by an LBNE WC (a LAr would be less sensitive than Super Kamiokande due to its smaller fiducial mass), and leaves a very limited range of lifetimes of up to about 4×10^{34} years for getting 3σ evidence.

The kaon from the second mode is below Cerenkov threshold, so the search for this mode in a WC detector consists of looking for the subsequent decay of the kaon, which is not as clean a signature as the original proton decay. The WC's improvement in this mode is expected to be only about a factor of two over Super Kamiokande. This mode, on the other hand, would produce a very clean signature in a LAr detector, where the original proton decay could be seen by the monoenergetic recoil kaon, followed by its decay. A LAr detector could make a 5σ discovery for a significant factor

(~5) of lifetimes beyond the current limits, and another factor of about 2 on that where it could see 3σ evidence.

2.3 SN Burst neutrinos

A type II SN in our galaxy would produce a large burst of neutrino events in either of the proposed detectors, as the (much further away) SN 1987a did in the IMB and Kamiokande detectors. This burst of neutrinos might turn out to be a once-in-a-lifetime chance to get a direct view of the internal workings of a supernova. A SN in our galaxy would produce tens of thousands of events in the proposed LBNE WC detector, and thousands in a LAr. The patterns seen would give interesting information on oscillation parameters, in particular the mass hierarchy. However, we may hope that these parameters would have already been determined by the long-baseline programme before the SN was observed. These events would be even more interesting in showing the time evolution of a SN, collective effects in the neutrino-sphere and the resulting proto-neutron star, information it would be difficult to imagine obtaining in any other way. The scientific payoff would be enormous. If Super Kamiokande is not running, then the much larger fiducial mass would clearly favour the WC option. If Super Kamiokande is running and therefore a large sample in a WC detector would exist anyway, there would be an advantage to having an independent data sample from a LAr detector, which has different flavour sensitivity.

3 WC detector

We list here, in bullet point form, what we consider the key strengths and challenges of the proposed WC detector, and the key risks which we think should be considered when making a technology decision. A similar list for the LAr detector follows in the next section.

3.1 WC detector – key strengths

- There is a long history of successful water Cerenkov detectors for this type of physics, most notably from the IMB, Kamiokande, Super-Kamiokande, and SNO experiments. This is a well-developed technology and has been used in two previous long-baseline neutrino oscillations experiments (K2K and T2K). The basic principles of a WC detector are well understood and are unlikely to yield any surprises.
- The LBNE collaboration contains broad expertise on water Cerenkov technology, including members of all of the water Cerenkov experiments listed above.
- The WC detector offers the largest achievable detector mass. It thus provides the largest sample of events to work with, which would bring significant benefits to atmospheric neutrino oscillation studies, supernova detection, relic SN neutrinos.
- This large event sample offers the potential to greatly improve the statistics to the extent that improved analysis techniques would allow non-QE events to be included in the signal. In their absence the two detectors, as proposed, have a comparable number of signal events. The advantage is size would be particularly important at low energies, where the CP-sensitivity is potentially high but the statistics are poor.
- The use of an open water tank makes access easy for a broad range of calibration devices, and substantial experience exists on how to calibrate a large water Cerenkov detector. This means that estimates of detector performance are likely to be well founded.

3.2 WC detector – key challenges

- The WC technique works best for simple final states, as it becomes difficult to properly reconstruct the overlapping Cerenkov rings from final states with many charged particles. The energy range of LBNE is not well tuned in this respect, as most of the cross-section at LBNE energies is for more complicated final states which currently contribute backgrounds rather than signals.
- The relatively poor rejection (compared to a LAr, see the figure) of (primarily) neutral-current background events produces a large background under the key second-maximum appearance peak.
- The current reconstruction algorithms are limited to unambiguous reconstruction of QE events only, resulting in low efficiency compared to the total neutrino interaction rate.
- The use of Cerenkov light for particle detection means that the Cerenkov threshold makes the detector blind to low-energy charged particles, which would hamper the reconstruction of some channels.
- Optimizing physics sensitivity for other topics such as solar or geo neutrinos would require costly upgrades to the detector.

- It would not be possible to run a WC detector as a near detector, requiring larger corrections to the measured near detector distributions in order to extrapolate them to the far detector.

3.3 WC detector – remaining significant risks in our assessment.

- Simulations to date assume a 5% systematic error in background normalization and no systematic error in background shape, both of which seem very optimistic. The poor state of our knowledge of the cross-sections for individual exclusive channels could easily result in a distortion of the energy spectrum of the mis-reconstruction background, thus altering the apparent ratio of the first to the second maximum appearance peaks and the shape of the peaks themselves, and furthermore does it differently for neutrinos and anti-neutrinos. This could lead to a false CP-violation signal (or mask a real one). Near detector measurements will help, but cannot eliminate this possibility, as the near detector will be unable to determine in every case what channel produced each background event, and therefore the extrapolation to the far detector is uncertain. The plausible size of this systematic has not yet been estimated.
- The construction of such a large WC detector requires a cavity of unprecedented size at large depth. This creates schedule, cost, and even project failure risks which should be carefully considered.
- The collaboration currently assumes a 40% increase in the light-collection efficiency from either concentrators or wavelength-shifting plates. However no actual final design exists and detailed simulations of the effect of such systems on the physics sensitivity have not been completed. If such light collectors turn out not to be feasible this would require a much larger number of phototubes to achieve the same physics return.
- Although the phototubes currently being considered are smaller diameter than those used in SuperKamiokande, and therefore are less susceptible to implosion, a full engineering evaluation of implosion risks and mitigation schemes has not been completed. This introduces additional uncertainty in the light collection efficiency.

4 LAr detector

4.1 LAr detector – key strengths

- The near-photographic imaging of events would allow reconstruction and particle identification for each track and excellent track/shower separation and π^0 rejection. This would allow unprecedented reconstruction of neutrino interactions. . This is the basis for the lower predicted backgrounds not arising from the intrinsic ν_e contamination of the beam, as can be seen in the figure. The excellent reconstruction capability could lead to background rejections even higher than currently assumed.
- The use of ionization rather than Cerenkov light removes the Cerenkov threshold and makes the detector sensitive to all charged particles.
- Many of the operational parameters, like the electron drift lifetime, can be calibrated *in situ*.
- The rich new data would attract significant global interest and supply many challenging analysis topics to engage the community, giving opportunities to young physicists to make a mark.
- There is no experience in operating a LAr detector of this scale underground. Its entirely new capabilities could lead to totally unexpected discoveries, which has happened many times in underground physics.
- The possibility of building a small LAr detector for use as a near detector should lead to reduced systematic uncertainties in the comparison of the near and far detector measurements.

4.2 LAr detector – key challenges

- There is no experience in operating a LAr detector of this scale anywhere, particularly underground. This could lead to delays/overruns due to unexpected problems.
- The detailed reconstruction of LAr data is still in a very early stage.
- Great care is needed to maintain overall cleanliness and purity to maintain the drift electron lifetime.
- It should be noted that a large LAr detector consists in the repetition of a large number of basic cells. This committee believes that most of the needed elements have been or will be tested in large set ups: cryostat, liquid purity, wire structure, HV, low temperature electronics. The extrapolation from the 600 ton of Icarus to 40kT may therefore be less risky than the factor 70 in mass seems to imply. However the new detector design will require extensive prototype testing for construction details, cryogenic systems, TPC and electronics optimization response measurements.
- The muon veto system assumed for shallow deployment must have extremely high rejection to maintain proton decay sensitivity.
- The design of a low cost sensor of the primary scintillation light for triggering on non-beam physics at low energy is not yet complete.
- The impact of spallation isotopes from neutron interactions in LAr at 800ft is potentially a large problem for the SN physics, and is not yet well understood.

4.3 LAr detector – remaining significant risks in our assessment.

- Simulations to date assume a 5% systematic error in background normalization and no systematic error in background shape, both of which seem very optimistic. The poor state of our knowledge of the cross-sections for individual exclusive channels could easily result in a distortion of the energy spectrum of the mis-reconstruction background which alters the apparent ratio of the first to the second maximum appearance peaks and the shape of the peaks themselves, and furthermore does it differently for neutrinos and anti-neutrinos. This could lead to a false CP-violation signal (or mask a real one). Near detector measurements will help, but cannot eliminate this possibility, as the near detector will be unable to determine in every case what channel produced each background event, and therefore the extrapolation to the far detector is uncertain. The plausible size of this systematic has not yet been estimated. The impact of this uncertainty for LAr is less owing to the smaller overall background.
- The assumed rejection efficiency of the muon veto needed for an 800-ft siting is aggressive and undemonstrated. This could result in a significant reduction in the fiducial volume which can be used for the critical $p \rightarrow K\nu$ proton decay channel unless the detector is located at the greater depth. Cosmogenic production may reduce sensitivity to new non-beam physics at the shallow level.
- The photon detector light collection system may need to be enhanced to allow efficient detection of the lowest-energy SN burst neutrinos and other low energy physics.

5 Conclusions and Recommendations.

The material presented in the previous sections is intended to be mostly factual. In this section we offer, as requested, our best scientific judgement of the relative merits of the two technologies.

- The proponents of both technologies have produced an impressive body of technical development and wide-ranging and sophisticated simulation and analysis work to support their proposed detectors.
- *In light of the presented materials the committee unanimously agrees that both technologies represent significant scientific opportunities, that either detector could be built at an acceptable level of risk, and that current knowledge supports the view that either is likely to deliver its expected performance, and that either detector would make world-leading measurements relevant to all of the major science goals.*
- By design, the performance of the two detectors for the headline long-baseline oscillation physics is comparable. Future analysis developments could lead to substantial improvement of the ability of the LAr detector to reject backgrounds not arising from the intrinsic ν_e contamination of the beam, while analogous developments could lead to a substantial increase in the efficiency for the WC detector to reconstruct more complex events and hence increase its useful rate. Given the relative maturity of the two technologies the committee feels that there is more scope for advances in the LAr case. The committee recommends that the collaboration should carefully judge which of the two advances is more likely, as this could have a substantial effect on the relative capability of the two detectors.
- The major unanswered question is the effect of background uncertainties on CP sensitivity. The lower background level should make LAr less sensitive to systematics in the backgrounds. In the view of the committee the greater ability of the LAr to reconstruct complicated final states may yield a further reduction in this risk.
- A significant issue in the long-baseline experiment is to cleanly measure the anti-neutrino sample from the large contamination of neutrino events (or, to a lesser extent, to do the converse). This requires a magnetized near detector, and it would be important to be able to make these measurements with the same target material in the near and far detectors. Therefore the potential to build a magnetized LAr detector at the near site seems a significant advantage for the LAr option.
- Given existing limits from Super Kamiokande, the best opportunity for a significant discovery in proton decay is in the $p \to K\nu$ channel, and in this channel the LAr detector has the clear advantage. The committee notes that the impact of continued SK data taking, and the desire for complementarity in p decay final states reinforces this conclusion.
- The greater size of the WC detector gives it a clear advantage for some of the other physics, in particular, for the SN burst measurement, although the LAr could see a striking signature of the hierarchy and give important information on collective phenomena in the neutrino sphere. If Super Kamiokande continues to run, the complementary information provided by a LAr detector in the event of a galactic SN would be valuable.

- The LBNE experiment will be the leading experiment at the Intensity Frontier. As such, very good "buy in" from the US high energy community is essential. Although it obviously did not conduct a survey of the field, the committee felt that the LAr, as a new technology on this scale, could create more opportunities to excite and thus recruit new young physicists in the project.
- The committee noted the value of enhanced infrastructure at the 4850 level at Homestake to a variety of other high-priority physics topics such as the search for Dark Matter and for neutrinoless double-beta decay. The committee felt that this added value to the overall US programme should not be discounted in the decision to put either detector at a deep site.
- The committee unanimously agrees that, that on the question of scientific capabilities, that the prospect for the LAr detector to refine our understanding of neutrino oscillations, and to be sensitive to unexpected new physics, exceeds that from the WC detector.

SECTION 3: **Response to the committee questions and comments on the written materials.**

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1. In our opinion the most important analysis topic is the effect on CP sensitivity of changes in the background shape arising either from uncertainties in the detailed cross-sections for individual exclusive final states or mis-modelling of the detector response. However we do not feel that the detailed simulations needed to quantify the likely systematic arising from this source could be realistically done in 1 week. One thing that could be done in a short time is to work out what particular channels lead to the largest contributions to the problematic background under the second oscillation maximum, and to vary the fraction of the total cross-section assigned to these channels by some conservative amount and see the effect this has on the CP sensitivity.

We agree that the evaluation of the background shape is the key part of the CP-violation (CPV) sensitivity of LBNE.

In the WCD analysis, where the backgrounds are larger, we used the variation in the Super-K multivariate selection efficiency and purity to vary the size and shape of the background and signal to background ratios to assess the impact on the CP violation sensitivities as presented in the talks by Ed Kearns and Mary Bishai. In addition, we have also performed an analysis (reported in the answer to WCD question 2) in which we only used single e-ring pre-selection particle ID with ***no multivariate analysis at all***. This results in a massive increase in background in WCD. The loss in sensitivity to CP violation is modest assuming we know the shape of the large background extremely well. The results of all these studies indicate that the exact shape of the expected background at this point is not critical for CP violation sensitivity, but that what is critical is how well the design of LBNE will allow us to predict the background shape at the far detector when the actual experiment is operating. Our ultimate goal is to perform this assessment with a complete Monte Carlo of the beam, and the detector, and use the data from the near and far detectors to evaluate the errors. We are now considering the following sets of techniques to study the background shape and acceptance in LBNE:

Determination of the background shape and acceptance using far detector data outside the signal region.

There are many different independent far detector data samples (outside the signal region) that we can use to assess the background shape and acceptance in the signal region. All of the methods using the far detector alone have kinematic biases, but are immune to detector mis-modeling. The kinematically most robust means to determine the background shapes is using the Near Detector. A combination of the Near Detector and Far Detector techniques will be needed. Some of these are:

1) Charge current ν_μ events with showers: Experiments have utilized these channels with the muon deleted in software to understand the detector performance on the remnant shower. This technique was recently used in the MINOS ν_e analysis to model NC hadronic shower shape in the near detector.

2) Exclusive channels in which a π^0 is clearly reconstructed. Recently, MiniBOONE was able to estimate the NC single π^0 background to the ν_e QE signal with an uncertainty of 5% using this technique in a Cerenkov detector.

3) For a fine-grained detector (LAr) an additional category of events is in which there is a clear separated upstream vertex.

4) The rejected events after the e/gamma separation can be used to determine the shape of the NC background (note: events that fail any of the likelihood cuts can be used in this way).

The above methods have been used in multiple experiments (MINOS, E776, E734, NOMAD, MiniBoone, etc) in the past with great success to obtain the background shape. Each of the above samples is expected to be large and will have a different mixture of final states. E734 and NOMAD have both demonstrated that sensitivity to mixing angle as small as ~ 0.003 is possible even in the presence of backgrounds.

Determining background shape and acceptance using far detector data and different beam tunes:

There is an additional interesting method available for LBNE that is not suitable for other experiments. This comes about because of the especially large size of the LBNE far detectors and the tunability of the beam. If the LBNE beam is tuned to be high energy the amount of expected signal can be made relatively low. Such a method has been used by MINOS using the their near detector. For LBNE such a tune can yield ~15000 (~60000) total interactions (NC+CC) for a 34 kT LAR (200kT WCD) detector without oscillations within 1 year. Such a large data set can be useful for background studies using the far detectors themselves.

Impact of different final states on shape of NC background:

For neutral currents, the shape of the background is determined mostly by the kinematics of the weak interaction. Since the NC has to be low Q^2, the NC event shape in visible energy must have a smooth falling shape even for resonant modes. This shape is significantly different than the double peaked signal spectrum in the wide-band beam. The shape below 1 GeV is sensitive to the content of multipion states. Using the results from the study of SK performance (Kearns), 80% of the background below 1 GeV is due to single pi0 events. A 30% uncertainty on the remaining 20% of the background will change the overall background shape below 1 GeV by 6%. This will have to adequately calibrated using the near detector data and far detector side-band.

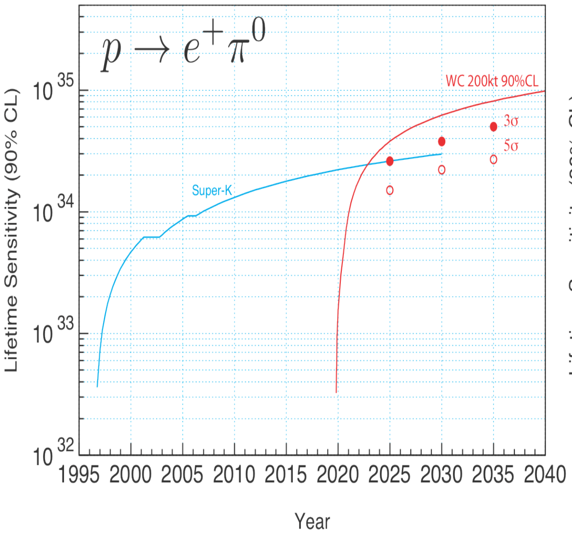
Determination of the background shape in Near Detector

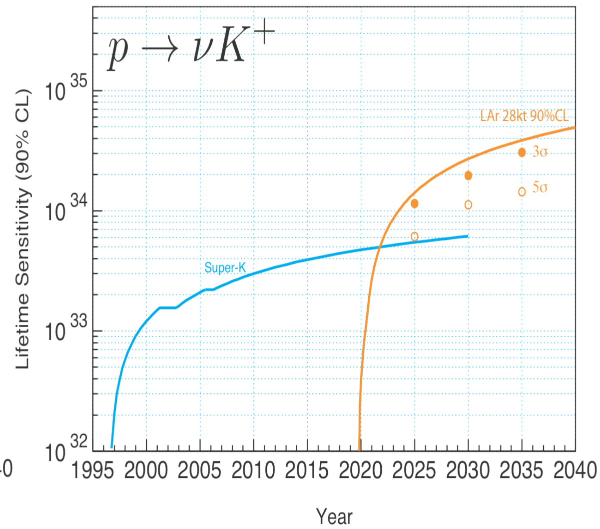
Obviously, the Near Detector (ND) will be our best way to determine background shapes, allowing for detector-dependent corrections in tracking and Near/Far spectral differences. The largest backgrounds for the WCD come from π^0 's in NC events, followed by beam-induced ν_e events. The LBNE Near Detector is designed to precisely measure the detailed kinematic distributions of the π^0 production in many different topologies (NC, high and low Y_{BJ} CC). The ND will distinguish NC from high-Y_{BJ} CC on an event-by-event basing (using the missing P_t vector).

The π^0 yield will be measured in neutrino-H20 target with a 5-10 times the statistics expected at the FD. Additionally, the ND will measure the electron-neutrino and anti-electron-neutrino CC. (NOMAD determined the (anti-) ν_e / ν_μ ratio with approximately 1% (10%) precision; the LBNE-ND is designed to perform an order of magnitude better.

2. Can you make a plot of PDK discovery potential for both detectors for both channels as a function of exposure and compare that to SK?

Here are the standard sensitivity curves for the 90% CL limit that would be set by an experiment as a function of time, assuming the experiment observes as many events as the expected background. Superimposed are sample points where LBNE could claim a 3-sigma or 5-sigma discovery. Here is a sample calculation. Suppose the true lifetime/branching ratio for e+ pi0 is 2.1e34 years. After 10 years, WC200 would have an expected background of 4 events, but would have also observed a signal of 8 events. The Poisson probability for 4 events to yield 12 is 0.0027, which is the p-value corresponding to 3-sigma. This calculation neglects systematic uncertainty. Note that if the lifetime is this large, rather than set a 90% CL limit, Super-K with a 0.7 Mt year exposure would have detected 3 or 4 events and would have an indication of about 2-sigma significance.





It is possible that these 4 expected background events in the WCD could be rejected at some level if a neutron tagging capability was added (e.g. via addition of gadolinium to the water). This is due to the fact that ~80% of proton decays in water are not expected to result in free neutrons in the final state. Detailed calculations have been carried out by Ejiri[1], but the reasons for this are easy to understand. Out of ten protons in the water molecule, two are free protons, two are in the 2s valence state of oxygen (hence decay would leave the nucleus already in the ground state), and four are in the 1p state, such that de-excitation via emission of a single gamma ray from the 2s->1p state is expected to dominate. Thus neutron emission is expected mostly only from the decay of 1s state protons.

[1] Phys. Rev. C 48 1442 (1993)

Less certain is the neutron yield from atmospheric neutrino interactions in the ~1-3 GeV range that constitute the background. Estimates range from 1-3 neutrons on average, due to both direct production via anti-ν CC interactions, and indirect production from nuclear final state interactions and π^{-}/μ^{-} capture. While these need to be ascertained by data, it is possible that a factor of two or more reduction in backgrounds might be realized, with a corresponding improvement in the detector reach.

3. It would be interesting to an analysis of the CP violation sensitivity from both experiments as a function of a lower-energy cut on the reconstructed neutrino energy. This would allow one to see whether the CP sensitivity is arising in this analysis primarily from the second-maximum or from the shape of the first maximum, which might have an influence on the desirability of proposed off-axis modification to the neutrino beam.

The LBNE oscillation maxima at 1300km are located at approximately 2.5 GeV (1st maximum) and 0.8 GeV (2nd maximum). The nue appearance probability is close to 0 at 1.25 GeV. Therefore, the energy region of the 2nd maximum is taken to be the region from 0.5 to 1.25 GeV. We do not include the region below 0.5 GeV in the calculation of LBNE sensitivities. We expect the WCD to be more sensitive to the region from 0.5 to 1.5 GeV due to the larger mass and large signal efficiency in this energy region. The nue CC effective mass (efficiency x mass) of WCD in the region 0.5-1.5 GeV is 100 kT, compared to LAD which has a corresponding nue CC effective mass of 27 kT. Figure 3a shows the expected neutrino event spectra in both detectors for $\sin^2 2\theta_{13}$=0.04, normal hierarchy 700kW, 5 yrs of running in neutrino mode. A comparison of the spectra in the region of 0.5 to 1.5 GeV reveals that the signal (δ_{CP}=0) in WCD is greater than 1 sigma above background for energies > 0.8 GeV, whereas signal and background separation in LAD is > 1 sigma only above 1.5 GeV.

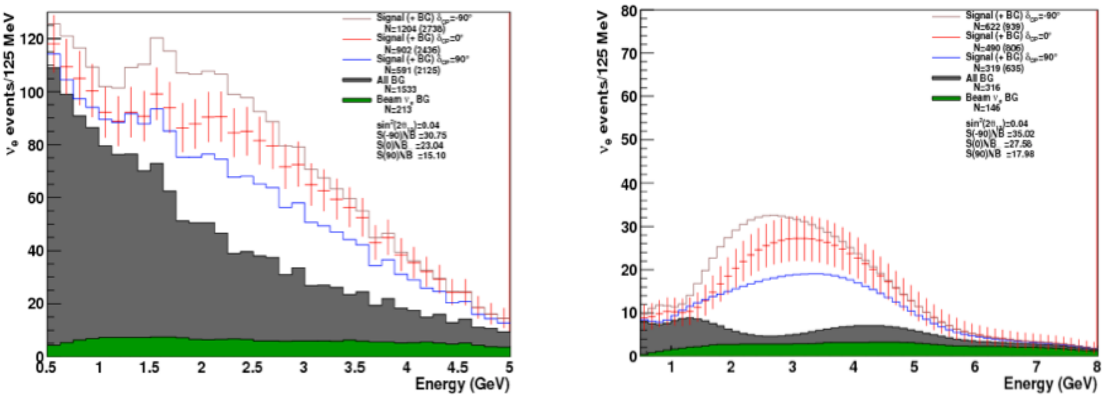


Figure 3a: The event spectra from 5 years of neutrino running at 700kW assuming normal hierarchy and $\sin^2 2\theta_{13}$=0.04. On the left is the spectra expected in 200kT WCD and on the right is the spectra expected for 34kT LAD.

To study the impact of the signal at the 2nd maximum on the oscillation analysis, we have re-calculated LBNE oscillation sensitivity projections computed using the GLoBeS framework by varying the lower energy bound on the signal region. Typically the GLoBeS signal region is defined as the region from 0.5 to 5 GeV. We used the following lower energy bounds and recomputed the sensitivities: 0.5, 0.8, 1.0, and 1.2 GeV.

Figure 3b shows the impact of this lower energy restriction on the CP violation sensitivity – assuming normal mass hierarchy - for a 200 kton WC detector (assuming SK-1 input parameters and a likelihood cut selected to retain 80% of nue QE signal events) and a 34 kton LAr detector (assuming the default parameters from the case-study, 80% ne CC efficiency and 1% nu NC and numu CC mis-identification rates). As the lower energy bound is increased, a small gradual loss in CP violation sensitivity is seen for both detectors, most notably for values of δ_{CP}>0. The effects are slightly larger for WC than for LAr as expected.

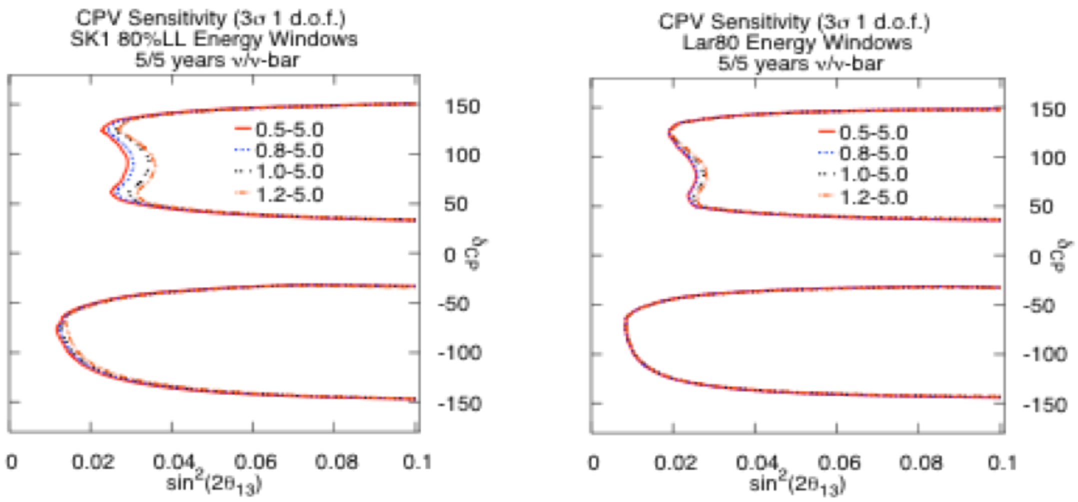


Figure 3b: CP violation sensitivity assuming normal hierarchy obtained with varying minimum energy bound in the analysis for a 200 kton WC detector (left) and 34 kton LAr TPC (right) operating at 1300km in 5+5 years of neutrino+antineutrino running in a 700 kW 120 GeV beam. Plots are shown on a linear scale as a function of sin22q13 and dCP. Plots provided by M. Bass (Colorado State University).

Figure 3c shows the impact on the mass hierarchy reach. For both detectors, the mass hierarchy sensitivity is more heavily effected, again the largest impact being for δ_{CP}>0 where the signal statistics are smaller and where one is relying on shape information to help resolve parameter degeneracies. Here, we see that the largest change in sensitivity occurs in going from a 0.8 to 1.0 GeV lower energy cut, hence highlighting the importance of the region in between the 1st and 2nd oscillation maxima.

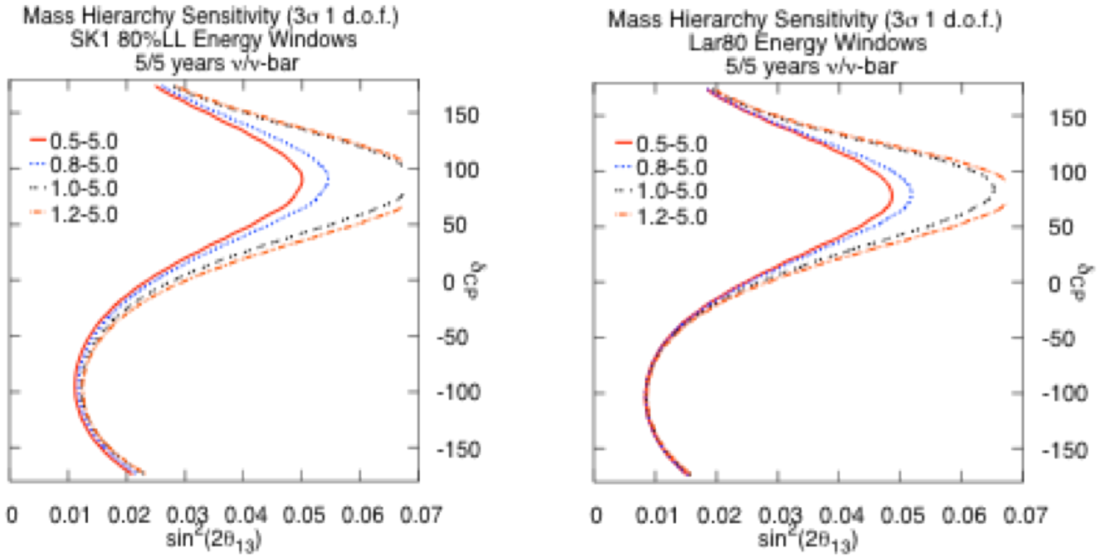


Figure 3c: Mass hierarchy reach with varying minimum energy cuts for a 200 kt WC detector (left) and a 34 kt LAr TPC (right) operating at 1300 km in 5+5 years of neutrino+antineutrino running in a 700 kW 120 GeV beam. Plots are shown on a linear scale as a function of $\sin^2 2\theta_{13}$ and δ_{CP}. Plots provided by M. Bass (Colorado State University).

Larger effects than this are seen (for both detector cases) if a 2 MW beam exposure is assumed and larger event statistics are present. Plots for 2MW are available upon request. From this study we conclude that most of the CP violation sensitivity is obtained from the shape information at the 1st oscillation maximum and the combination of neutrino and anti-neutrino running for all values of δ_{CP}. The sensitivity to the mass hierarchy is very dependent on the 2nd maximum in the region $\delta_{CP}>0$. Improvements in the beam design that would sacrifice flux at the 1st maximum to increase the flux at 2nd maximum significantly (like off-axis beams) would benefit mass hierarchy sensitivities but are detrimental to the CP violation sensitivity. As will be discussed in the response to question 4 for both detectors, the beam design policy of LBNE is currently focused more on improving S:B at the 2nd maximum using modest flux increases at the 2nd maximum coupled to large background reductions while minimizing reductions in flux at the 1st maxima.

4. Beam group question: How much flexibility does exist in the beam design, for instance by going slightly off-axis, to increase the low-energy neutrino flux at the cost of a reduction in the overall rate?

The LBNE beam design is still at the conceptual phase and there still exists a great deal of flexibility, particularly in the design of the target and focusing systems which have not been fully optimized for LBNE. We will summarize some of the possible improvements being considered. The goal of the LBNE beam optimization studies summarized here was to improve the signal to background by reducing the flux of neutrinos > 4 GeV and achieve some modest gains in flux at the 2nd maxima without sacrificing the neutrino flux at the 1st oscillation maxima. For purposes of this discussion, we consider the neutrino energy range from 0.5 to 1.25 GeV to be the region of the 2nd maximum and the range from 1.25 to 5 GeV to be the region of the 1st maximum. The numbers given here are for $\sin^2 2\theta_{13}$=0.04, δ_{CP}=-90, for a 200 kt WCD using the SK 80% LL cuts. The study was done for WCD because the signal to background optimization is more critical for that detector, but the results also apply to LAD. The ν_e appearance spectra in WCD for the nominal beam configuration is shown in figure 1 below.

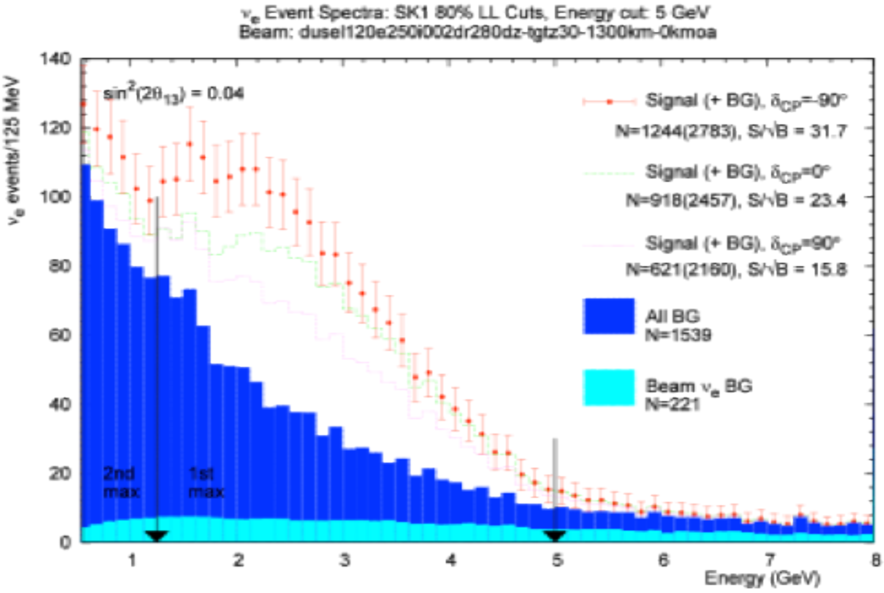


Figure 1: Signal and background at the nominal beam configuration.

At 1300 km, off-axis beams are not feasible because the loss of statistics in the region of the first oscillation maximum is too great. A beam that is 0.5° off-axis reduces the signal at the first maximum by about 30% while increasing the signal at the second maximum by only 6%. (See figure 2. below) A beam that is 1° off-axis reduces the signal at the first maximum by almost 80% and a beam that is 0.25° off-axis is too close to the nominal configuration to make any difference. Background is significantly reduced by an off-axis beam, but for LBNE the loss of statistics is too great. We have already demonstrated using the SuperK multivariate analysis technique that it is possible to improve the signal to background ratio at the expense of statistics at the analysis level, by applying tighter cuts. It is easy to change the analysis but almost impossible to change the beamline design once the experiment is running.

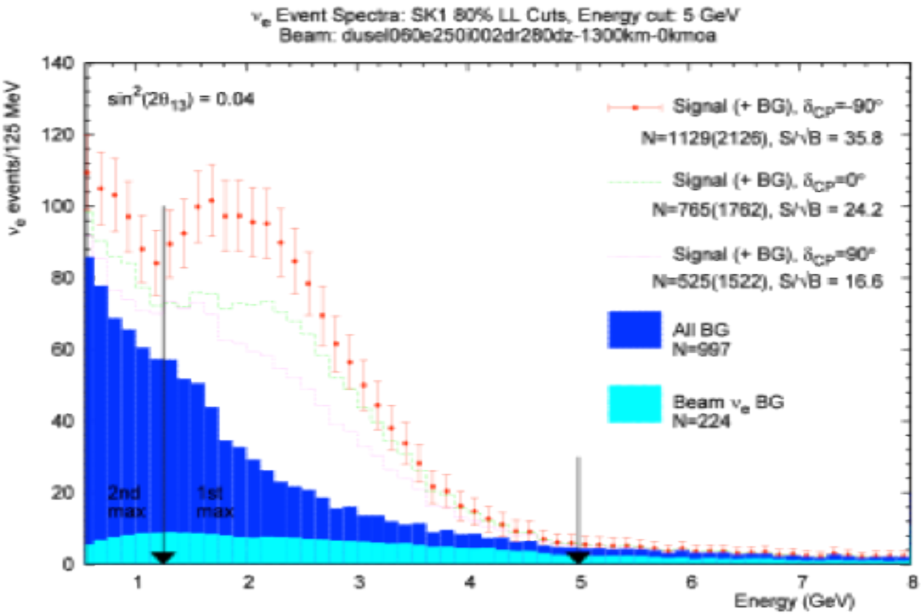


Figure 2: 0.5° off-axis beam.

For the same power, lowering the beam energy to 60 GeV and fully embedding the target in the parabolic NuMI horn 1 results in a 27% increase in the number of low-energy neutrinos relative to the nominal beam. The loss of neutrinos at the first maximum is about 14%. The signal to background ratio is improved for all energies. (See Figure 3.) For a beam power of 700kW, it is technically more difficult to fully embed the 80cm graphite target within the parabolic NuMI horn - which is currently the best focusing design considered for LBNE. In addition, it is not possible to achieve the same beam power at lower energies with the baseline 700 kW LBNE design (ANU upgrade), but with ProjectX, there is only 15% loss in beam power when the primary proton beam energy is reduced from 120 GeV to 60 GeV (see Figure 4.)

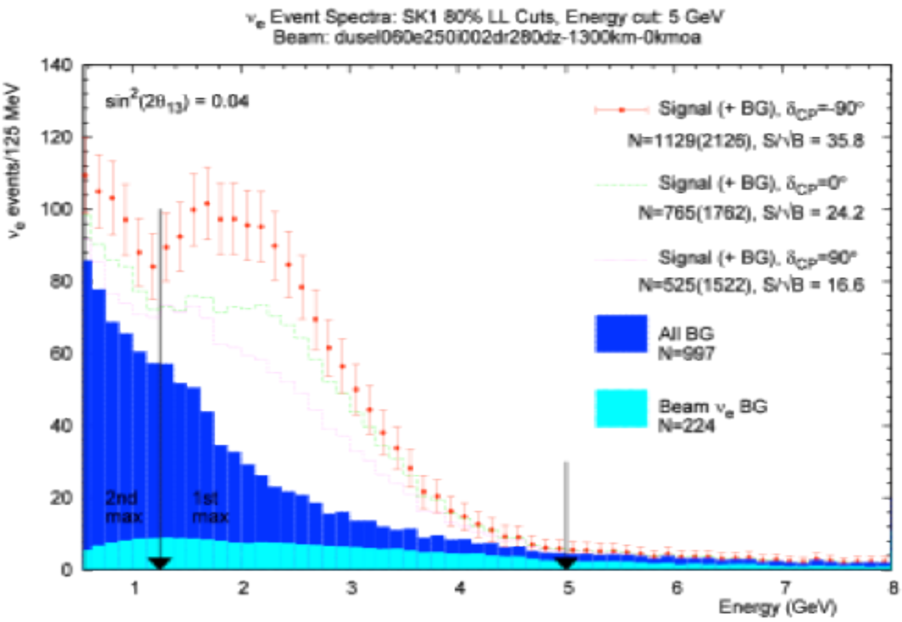


Figure 3: 60 GeV beam and imbedded target.

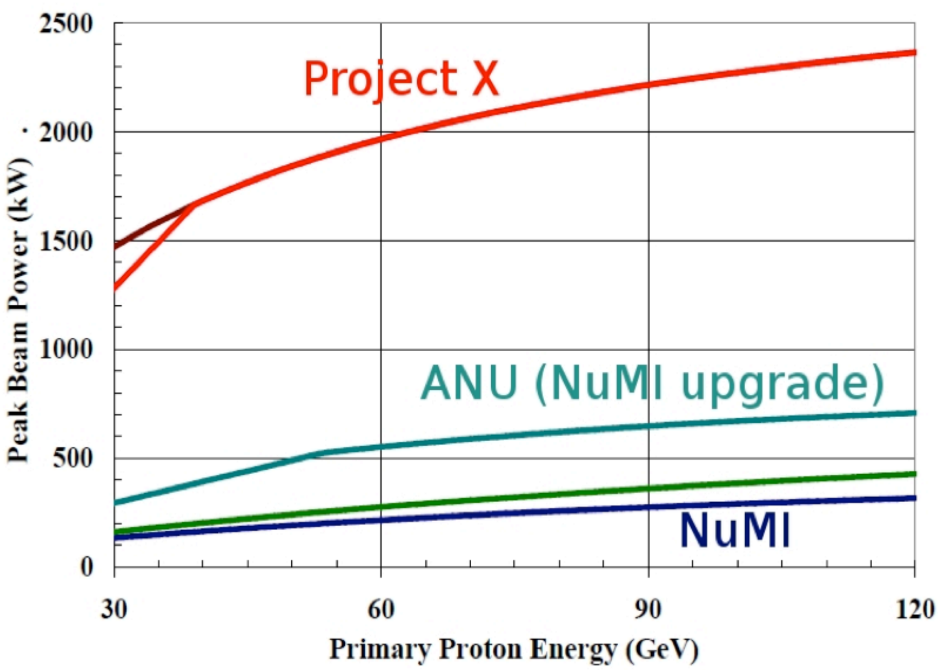


Figure 4: Beam power versus proton energy

One possible compromise that is technically feasible is to lower the beam energy to 90 GeV and use a hybrid graphite-tantalum target (40 cm graphite followed by 23 cm Tantalum or Tungsten). For a 90 GeV beam it is possible to get close to the same beam power as the 120 GeV beam (with ANU Main Injector upgrade), and the hybrid target is smaller and therefore easier to embed. This configuration results in a 21% increase in the number of of low-energy neutrinos and a 25% decrease in number of neutrinos in the region of the first maximum. The signal to background ratio under the second maximum improves from 0.2 to 0.4 and under the first maximum improves from 1.1 to 1.6. The improvement in the signal to background ratio is similar to the 60 GeV beam. (See Figure 5.)

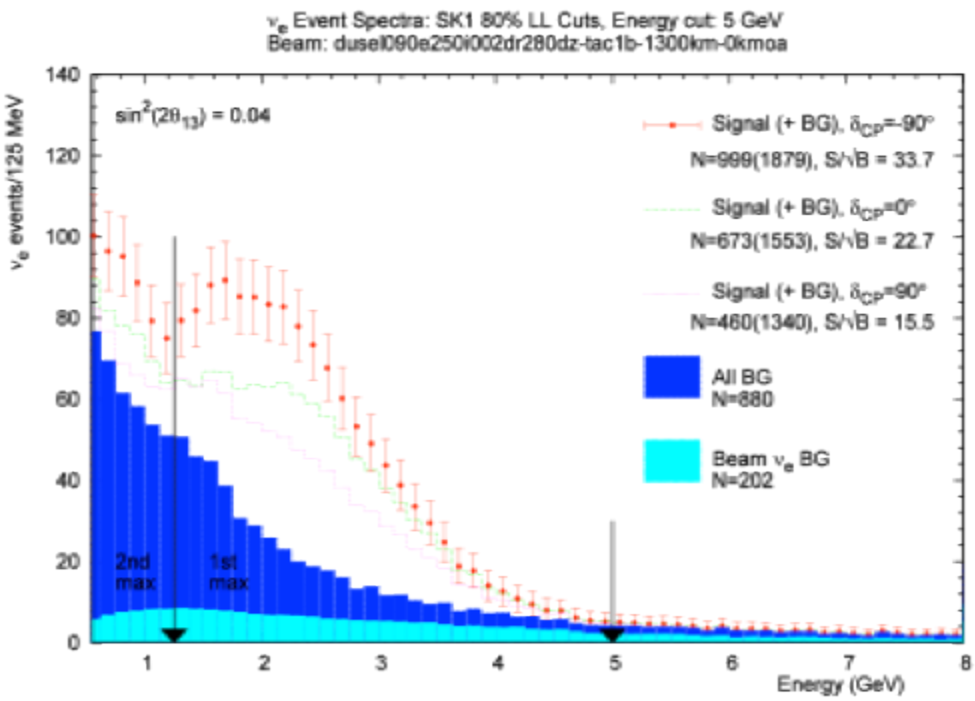


Figure 5: Hybrid target and 90 GeV beam.

In summary there is plenty of flexibility in the beam design. We have studied some feasible schemes to increase the low-energy neutrino flux by 20 to 30% while simultaneously improving the signal to background ratio from 0.2 to 0.4 in the region of the 2nd maxima. This can be achieved while sacrificing less than 25% of the signal at the first maximum, with significant improvements in signal to background at the first maximum as will. This can be accomplished by lowering the beam energy and/or modifying the target placement and target design. Small off-axis beams do not significantly improve the yield of low-energy neutrinos for LBNE.

Water Cerenkov:

1. What is the baseline design? There were simulations shown for a variety of different configurations of the detector, however it would be useful to have a baseline design for all simulations. We assume this baseline design is 200 kT, 37k 12-inch HQE phototubes, no light collectors, no acrylic implosion protection. It would be good to see a table showing what simulation results are available for the baseline design and what are based on extrapolations from other designs.

The baseline design is a 200 kt tank with 29K 12" HQE PMTs. We assume some Light Collector (LC) system which is assumed to add 40% to the light collection of each tube. There will be an implosion abatement system but, pending further tests, it is undecided the exact form of this system. It could range from acrylic covering as in Super-K to a housing system that absorbs or otherwise reduces energy available for the shock wave. The simulation is very flexible and many simulations were done as we narrowed down to our baseline design. However, for the purposes of what was presented to the committee, the following are the relevant parameters used for simulation and analysis:

Description:	Tools
Quoted Sensitivities	Flux re-weighted event-by-event SK-II MC was used to extract the efficiencies used by GLOBES. Further simulation efforts designed to study the performance of various options are designed to match this light collection and performance.
Basic WCSim simulation and performance arguments.	Were based on both the SK mode (used for tuning) and a 100 kt tank with 10" HQE tubes and 12% coverage designed to match the SK-II light collection ability. This work was done when two 100 kt tanks were envisioned.
Low-Energy Threshold Studies.	Also based on the 100 kt tank described above.

In order to do the scaling to our reference design and determine the correct number of tubes while the full simulation is being validated for this new configuration, a standalone water Cherenkov light propagation Monte Carlo previously validated against WCSim for the 22.5 and 100 kt cases was used along with the measured differences in QE for the 12" vs 10" tubes. Figure 4 shows the results of this Monte Carlo calculation for the 200 kt case.

Note: The decision to use LC is still being studied. If we do not achieve the required performance we will revert to using only PMTs

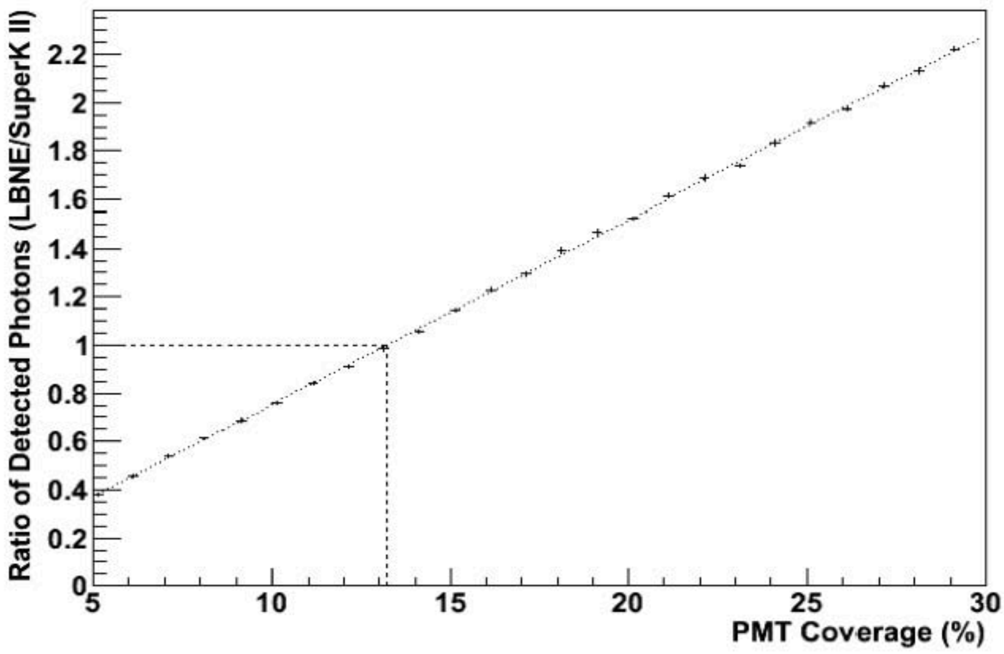


Figure 4: Ratio of Detected Photons (LBNE/SuperK II)

2. The multivariate analysis for background reduction is based on variables where the simulation seems to poorly reproduce the data (slide 20 of Ed Kearns' talk on SK inputs). We would like to see the change in efficiency when the simulation is repeated with the input distributions reweighted to reproduce the observed distributions. After the reweighting, are the results stable when trading efficiency for rejection?

The SuperK MC that was compared to the data on slide 20 of Ed Kearn's talk is the previous generation of the SuperK MC. This version was used for the studies in the Interim PWG Report and the Case Study reports. Given the known deficiencies of the older MC, the LBNE Long Baseline Physics Working Group has spent the last several months implementing the log-likelihood performance from the updated 2008 SuperK MC (F. Dufour et. al., Phys. Rev. D.81 0930001 (2010)) in the GLoBeS framework used to compute LBNE sensitivities. The results of this effort were presented to the review committee during the Science Capability meeting. The LBNE WCD is expected to perform differently from SuperK, so even if the SuperK MC perfectly reproduces the SuperK data, there is no guarantee that it will match the LBNE detector performance. To truly understand, and model, the systematic uncertainties on the multivariate analysis that could arise from detector mis-modeling in LBNE, the analysis has to be carried out using the detailed LBNE WCD detector simulation. This work is currently in progress but will take approximately a year to complete.

To address the committee's question on a short time scale, we have performed a simple study where we have removed the multivariate analysis selection from the LBNE oscillation sensitivity calculation altogether. Thus, we use only the SuperK selection efficiencies and detector response obtained using the simple single e-ring pre-selection criteria as discussed in Ed Kearn's talk. Although this is an extreme variation (we can already obtain a much better performance from the LBNE detector with a simple visual scan), it allows us to see what overall impact the multivariate analysis (log-likelihood) has on the long-baseline oscillation sensitivities in LBNE. Figure 1 shows the resultant event spectra (normal hierarchy, neutrino running) if only the pre-selection is applied compared to the spectra obtained after the log-likelihood selection preserving 80% of νe QE is applied. Although the ratio of signal/background is significantly degraded, the signal at the 1st maximum is still clearly visible above the background. Figures 2 and 3 show the impact of removing the likelihood cut on the CP violation and mass hierarchy sensitivities. In this study there is a 5% systematic uncertainty applied on the overall background normalization, and there are no shape uncertainties applied to the background.

Given that the background shape is assumed to be exactly known within statistical uncertainties , the removal of the likelihood cut on the sensitivity to CP violation has the greatest impact at δCP>0, where the S:B at the 2nd maximum is the most affected. With no log-likelihood cut, the signal at the 2nd maximum is no long distinguishable from background (see the answer to question 3 for both for a more detailed discussion of the impact of the 2nd maximum on sensitivities). The impact is that the worst 3 σ CP violation sensitivity point at δcp=90° moves from $\sin^2 2\theta_{13}$=0.025 to $\sin^2 2\theta_{13}$=0.035. The degradation in sensitivity is relatively small for CP violation because it is driven by the shape of the signal at the 1st maxima, which is still visible above background, and because we have assumed no uncertainty in the background shape.

The impact on the mass hierarchy reach (Figure 3) is quite drastic for values of δCP>0 where the sensitivity is driven by the signal/background at the 2nd oscillation maximum which is needed to break degeneracies.

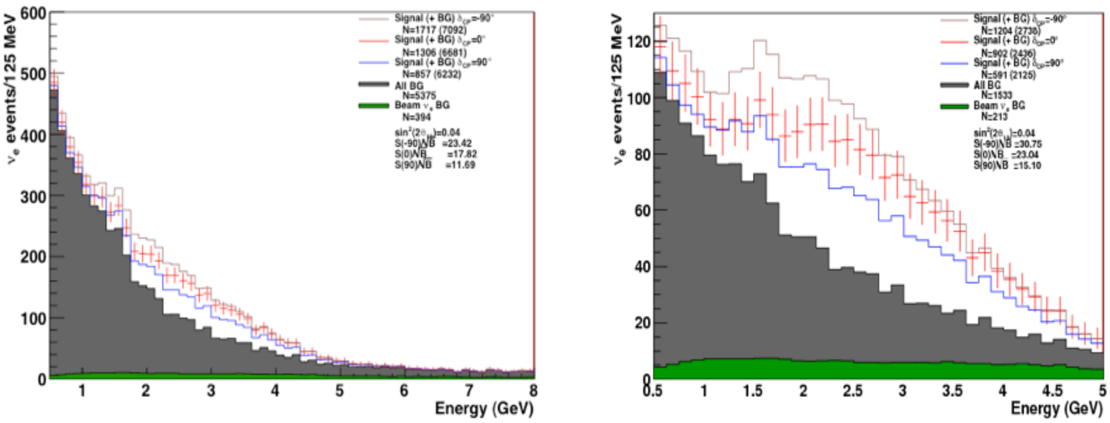


Figure 1: νe event spectra expected in a 200 kt WC detector operating at 1300 km in 5 years of neutrino running at 700 kW in a 120 GeV beam assuming a normal mass hierarchy, $\sin^2 2\theta_{13}$=0.04, and several representative values of δ_{CP}. Results are shown assuming only the pre-selection cuts are applied (left) and after the log-likelihood selection preserving 80% of ne QE is applied (right). Plots are from M. Bass (Colorado State University).

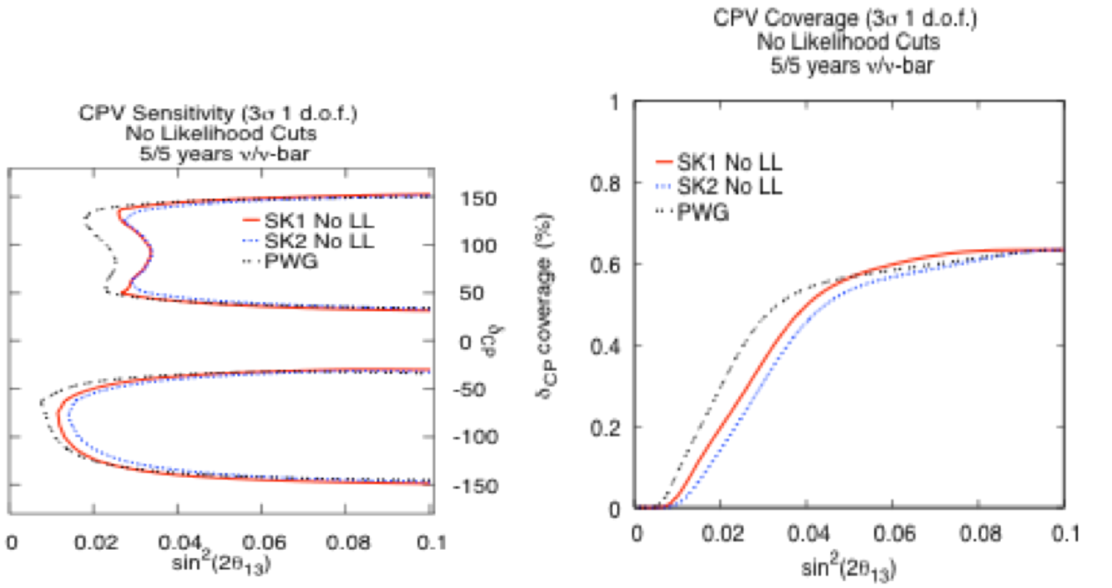


Figure 2: Impact of removing the likelihood cuts on the CP violation sensitivity. Plots show the sensitivity to CP violation at 3σ CL for a 200 kt WC detector operating at 1300 km for 5+5 years of neutrino+antineutrino running in a 700 kW 120 GeV beam as function of , $\sin^2 2\theta_{13}$ and the δ_{CP} phase (left). Also shown is the projection as a function of the fraction of δ_{CP} values (in %) that are covered by the measurement (right). Both plots are provided on a linear scale. In black is the sensitivity from the case study (labelled "PWG") which includes the application of both pre-selection and likelihood cuts. Additionally shown is the sensitivity with the new Super-K Monte Carlo inputs assuming only the pre-selection is applied for both SK-1 (red) and SK-2 (blue). All projections assume a 1% (5%) signal (background) normalization uncertainty. Plots are from M. Bass (Colorado State University).

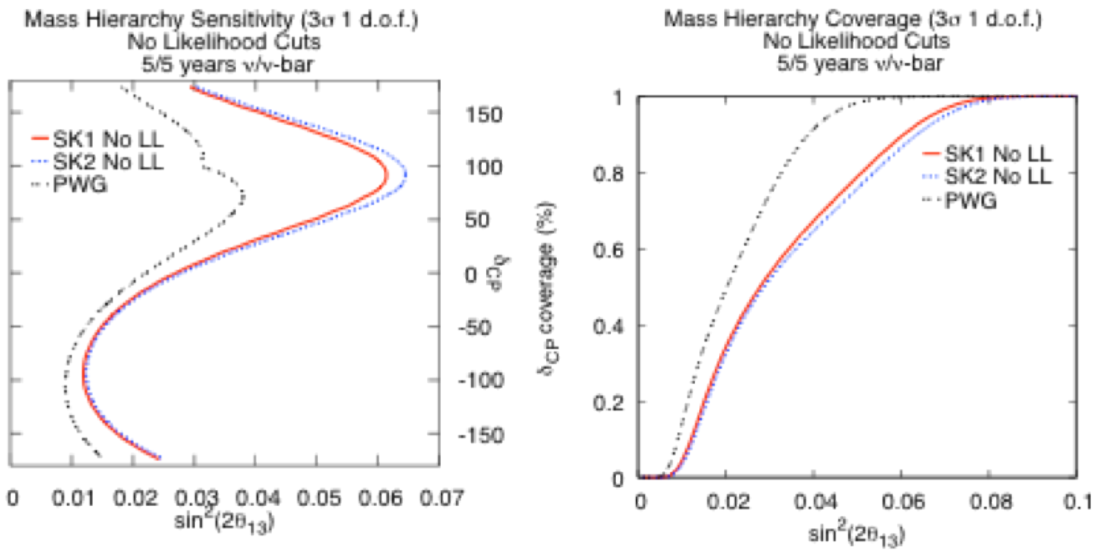


Figure 3: Impact of removing the likelihood cuts on the mass hierarchy reach. Same plotting convention as Figure WCD-2b. Plots are from M. Bass (Colorado State University).

It should be noted that, even with the removal of the likelihood cut, the mass hierarchy and CP violation sensitivity can be appreciably improved if an alternative beam configuration is adopted which reduces the NC background by a factor of 2 with a modest decrease in the neutrino flux at the 2nd maximum, for example, running at 90 GeV with a hybrid graphite-tantalum target (see the answer to question 4 for both). Those plots can be made available upon request.

Liquid Argon:

1. What is the spallation background at low energies at 800ft? What is it at 4850? How is this calculated (i.e., what spallation products are taken into account)?

Cosmic ray spallation of argon can produce isotopes which undergo radioactive decays resulting in events in the few to few tens of MeV range; these can be an issue for solar and supernova neutrino detection. At present very little work has been done to evaluate the low-energy spallation-induced background. We found essentially no information in the literature on muon spallation of argon (there are however some measurements of proton spallation cross-sections for a limited range of proton energies.) There are some ~85 possible nuclear fragments of argon which beta-decay with half-lives > 1 ms and with Q values > 4 MeV; the Q values range up to 21 MeV. Presumably those with very fast decays can be vetoed by association with muons; of the ~24 spallation isotopes with half-lives > 1 second, the Q values do not exceed 11 MeV. To estimate the distributions of the different fragments, we can make preliminary estimates using proton spallation information (although have not done so yet). A program to measure isotope production in argon could also be envisioned.

Reactions induced by fast neutrons from CR muons are a common form of cosmogenic backgrounds. The table below shows some at common neutron-induced products via (n,p), (n,d), (n,g), (n,α) and (μ-,ν). Of particular worry is ^{40}Cl, which has a 7.5 MeV β^- endpoint and a 95 second half-life. The long half-life makes rejection via tagging the parent muon very difficult, even in a fine-grained detector. With a measured near-surface fast (>5 MeV) neutron flux of 3.9×10^{-2} cm^{-2}s^{-1} (Mei, et al 2008), and ENDF cross section in the range 5-20 MeV of about 12 millibarns, the expected ^{40}Cl production rate (= to decay rate when in equilibrium) would be ~300,000 per second in a 40 kt liquid argon detector. Note that this rate is for the altitude of Los Alamos. It is roughly a factor of three less at sea level, or about 100,000 per second. At the 800-foot level, one can estimate the production via simply scaling the muon flux and correcting for the spectral difference using the empirically observed $\langle E_\mu \rangle^{0.7}$ dependence. The vertical muon flux has been measured on the 800 level to be 2.7×10^{-6} cm^{-2} s^{-1} sr^{-1}, as compared to the sea level value of 1.6×10^{-3} cm^{-2} s^{-1} sr^{-1}. At the 4850 level it is calculated to be 3.9×10^{-9} cm^{-2} s^{-1} sr^{-1}. The mean energy at these three locations is very roughly 5, 50, and 300 GeV.

Therefore the expected ^{40}Cl rates at 800 and 4850 are very roughly 10^5, 500, and 5 Hz in a 40 kt LAr detector.

Table 1 Isotopes from common neutron induced reactions

40-Ar (99.6%)	mechanism	daughter	decay	lifetime	endpoint	br to g's	comment
	(n,p),(mu,nu)	40-Cl	e-	1.35m	7.48	0.09	problem due to 7.48 MeV & 95 sec half life
	(n,d)	39-Cl	e-	55.6m	3.44	0.07	83% br to 1.52: continuous 3.44 MeV e- from g.s.
	(n,g)	41-Ar	e-	109m	2.49	0.0083	99% br to 1.29
	(n,alpha)	37-S	stable				no problem
38-Ar (0.063%)							
	(n,p),(mu,nu)	38-Cl	e-	37m	4.92	0.58	
	(n,d)	37-Cl	stable				no problem
	(n,g)	39-Ar	e-	269y	0.57	1	no problem - low Q
	(n,alpha)	35-S	e-	87.5d	0.19	1	no problem - low Q
36-Ar (0.337%)							
	(n,p),(mu,nu)	36-Cl	e-	301000y	0.71	1	in equilibrium
	(n,d)	35-Cl	stable				no problem
	(n,g)	37-Ar	EC	35d	0.81	1	no problem - low Q for e+ so EC only
	(n,alpha)	33-S	stable				no problem

Thus detection of SN burst neutrinos below ~10 MeV (endpoint of 7.5 MeV plus resolution) can be done only on a statistical basis at 800 feet, but should be relatively easy at 4850 feet. This study does not include other possible spallation sources, so an actual measurement in a surface detector should become part of the LAr prototyping program.

*2. Can you tabulate some examples of historic performance of muon veto systems to justify the assumption that a 10**-5 rejection can be achieved with the design shown? The only muon veto which we know achieved 10**-5 was LSND, but that was a very different design.*

We have not been able to find historic examples of muon veto systems with 10^-5 rejection efficiency. However, since the SciCap review, two independent toy Monte Carlo studies that perform ray tracing through the proposed veto configuration have found that, for all angles and positions across the detector, there is always at least one line segment in a veto cell of path length greater than ~3.4 cm. These studies use the correct veto cell geometry of three rows of 8" x 4" x 1/2" steel tubes with a 3mm thick walled PVC tube insert, and each row is staggered by 1/3 of the width of the cell. The attached figure shows an example of the veto cell geometry and configuration, and an example of a line that has close to the minimal path length.

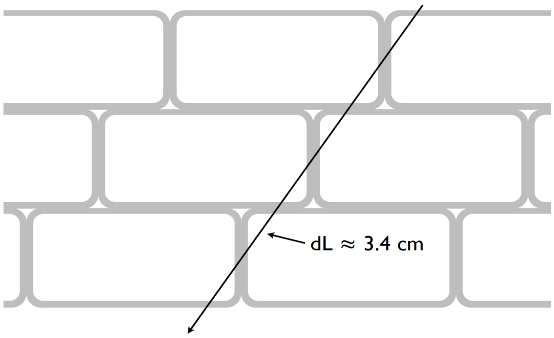


Figure 1: Geometry of the veto counter

From the CDR, we expect a vertical muon passing through the far end of a 9m-long veto tube to produce ~180 pe (the path length here is ~7 cm). A single hit is therefore enough to detect a muon. From the above toy MC studies, Therefore a single hit with a path length of 3.4 cm at the far end of a 9m-long veto tube should produce ~87 pe. The probability that such a muon track would fall below a threshold of 15 pe is 10^-15.

3. Can you explain in more detail the consequences for the effective fiducial volume for PDK if the veto does not achieve the planned rejection? What is the effective fiducial volume for p -> Kν as a function of rejection efficiency?

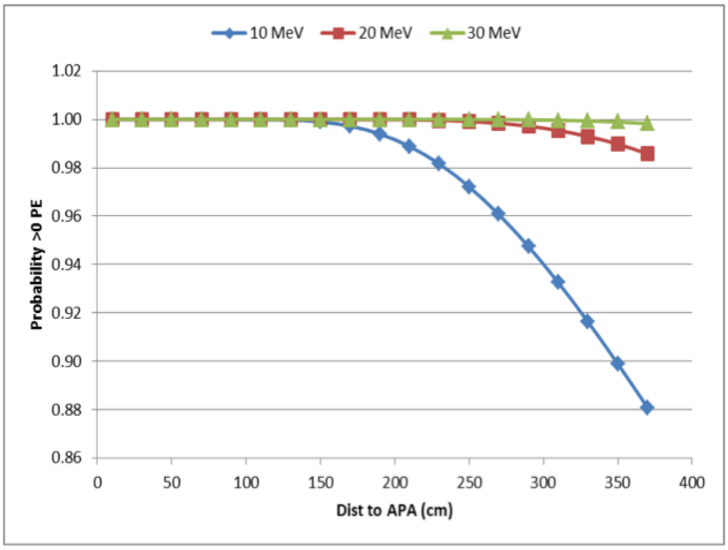
The general estimate process has been as follows: Results from the Bueno paper are used for the background at deep depth. Then an estimate is made for the "shallow" depth assuming an exponential shape of the distribution of K_L's from the edge. Production rate was presumed to scale with muon rate. This study has not been completed.

4. Can you state the impact on each physics goal (especially low-energy topics like SN burst neutrinos and solar neutrinos) of the detection efficiency of the photon detection system?

The presenter (Baller) gave a somewhat pessimistic view of the capabilities of the light collection system. The conclusion made from the plot of NPE vs distance to APA presented at the review was that a 10 MeV electron would only be detected if it occurred within 180 cm from the APA.

One significant assumption used in making this plot is that only the "fast" scintillation light (τfast = 6 ns, Nfast/Ntotal = 23%) would be used. The "slow" component of the scintillation light (77%) is emitted with a characteristic decay time constant of 1.6 µs [T.Doke, NIM A291 (1990) 617-620]. We will design the electronics to integrate both fast and slow components and improve the light yield significantly. Also, recent work on the cost estimate has allowed us to increase the density of light collecting paddles from 6 per APA to 10 per APA.

The plot shown below incorporates these corrections and shows the Poisson probability of observing at least one PE as a function of distance from the APA for 10 MeV, 20 MeV and 30 MeV minimum ionizing particles. The capability of the light collection system is considerably improved for supernova detection compared to that presented at the review. Given the current budget guidance, we do not propose to enhance the performance of the light collection system to enable the study of solar neutrinos. The light collection system is not strictly required for neutrino oscillation studies, although it would provide useful information to measure the neutrino time-of-flight. The performance of the light collection system is more than adequate for proton decay studies, which would have an energy deposition of several hundred MeV.



5. The errors assumed in table 4-3 are extremely conservative. To demonstrate the potential power of the technique it would be useful to see sensitivities recalculated assuming errors equivalent to the best anyone has demonstrated to date for the particular quantity.

We assume what's meant are "efficiencies" rather than "errors" as Table 4-3 in the LAr case study presents the detection efficiencies for various signal and background processes and not their uncertainties. Below we consider a feasible "best case" scenario where a 95% ν_e signal efficiency is achieved combined with a 0.4% background contamination (meaning 0.4% of ν_μ NC and 0.4% of ν_μ CC events are mis-identified as ne candidates). Figures 1 shows the change in the expected event spectra between the case study assumptions and this "best case" example.

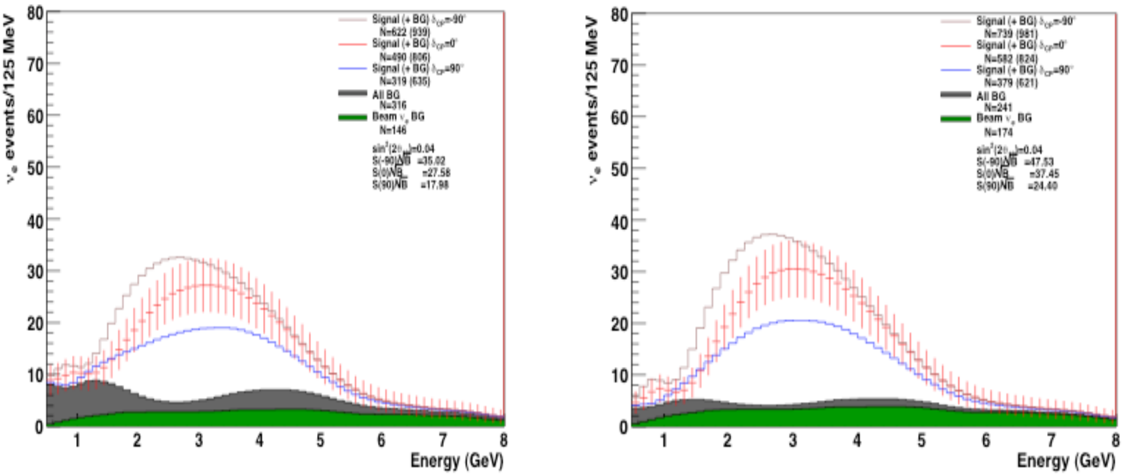


Figure 1: ν_e event spectra expected in a 34 kt LAr detector operating at 1300 km in 5 years of neutrino running at 700 kW assuming a normal mass hierarchy, $sin^2 2\theta_{13}$ = 0.04, and several representative values of δ_{CP} The left panel shows the results with the case study assumptions: 80% of ν_e events are assumed to be correctly identified while 1.0% of ν_μ NC and ν_μ CC events are mis-identified as ν_e candidates ("80%/1%" combination). The right panel shows the same but for a 95% ν_e efficiency and 0.4% ν_μ NC and ν_μ CC mis-identification rate ("95%/0.4%" combination). Plots are from M. Bass (Colorado State University).

Figures 2 and 3 show the CP violation and mass hierarchy reach with these assumptions. Not surprisingly the 95%/0.4% case is superior in all cases. The fact that the 95%/0.4% projections are not significantly improved beyond the 70%/0.4% case suggests that the intrinsic ne backgrounds have become the limiting factor in this case.

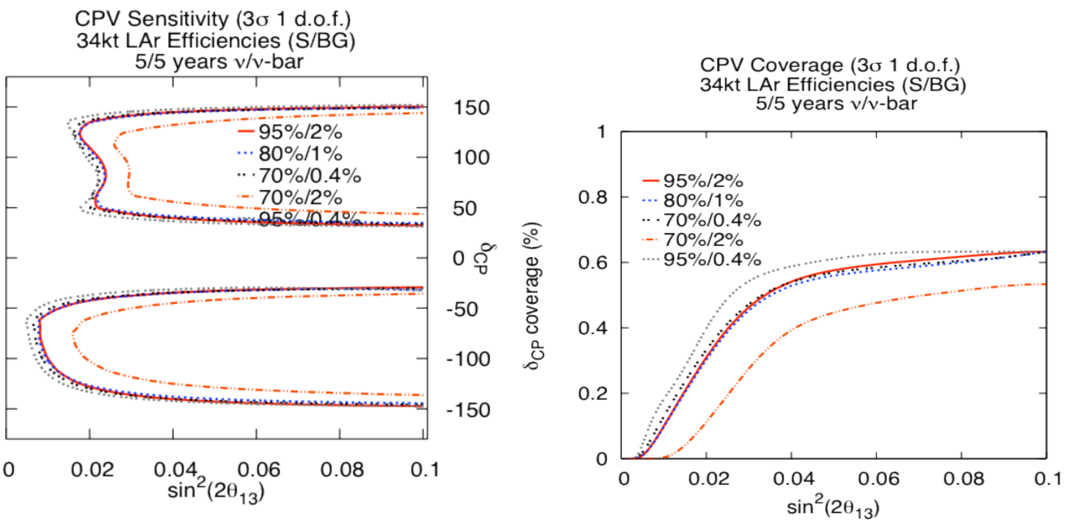


Figure 2: Sensitivity to CP violation at 3s CL for a 34 kton LAr TPC operating at 1300km for 5+5 years of neutrino+antineutrino running in a 700 kW beam as function of $sin^2 2\theta_{13}$ and both the δ_{CP} phase

(left). Also shown is the projection as a function of the fraction of δ_{CP} values (in %) that are covered by the measurement (right). Both plots are provided on a linear scale. Here, five cases are considered. The first number in the legend refers to the ne signal (and hence intrinsic ne beam background) efficiency. The second number refers to the percentage of ν_μ NC and ν_μ CC events that are mis-reconstructed as ν_e candidates. What's new is the addition of the 95%/0.4% projection. This means that 95% of all ν_e events in the fiducial volume are identified and reconstructed while 0.4% of all ν_μ NC and 0.4% of all ν_μ CC are mis-identified as signal. All five projections assume a 1% (5%) signal (background) normalization uncertainty. Plots are from M. Bass (Colorado State University).

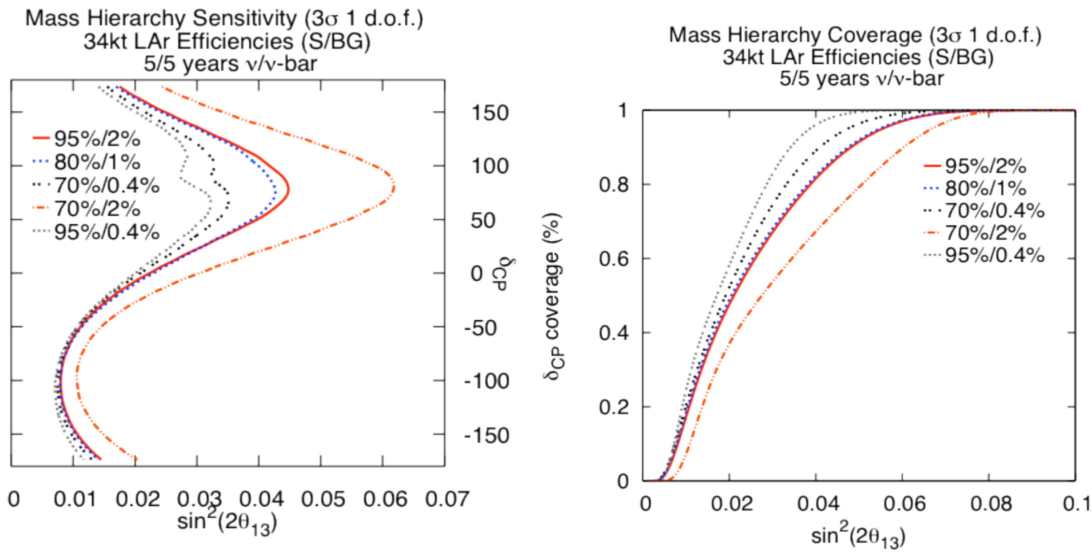


Figure 3: Sensitivity for LBNE to resolve the neutrino mass hierarchy at 3s CL for a 34 kt LAr TPC operating at 1300 km for 5+5 years of neutrino+antineutrino running in a 700 kW beam plotted as a function of $\sin^2 2\theta_{13}$ and the δ_{CP} phase (left). Also shown is the projection as function of the fraction of δ_{CP} values (in %) that are covered by the measurement (right). Same convention as Figure 1. Plots are from M. Bass (Colorado State University).

6. What is the sensitivity to neutrinos from relic supernovae at 800ft and 4850ft?

The sensitivity to relic supernova neutrinos at either depth is poor, mainly because the mass is relatively small, and event rates are very low in the 18-30 MeV "window" region between irreducible backgrounds from solar *hep* neutrinos and atmospheric neutrinos. About 0.3-2.2 signal events per year (with a rather flat spectrum), and 0.2 atmospheric neutrino background events per year, would be expected in 34 kt of LAr. The cosmic ray spallation-related backgrounds are poorly known (although may not have energies exceeding 11 MeV or so; see question 1), and the ability to tag CC ν_e events against background using de-excitation gammas is also poorly known at this time. If signal efficiency is high and background is low, this measurement might be conceivable; but even at the deep site, the signal rates seem low enough to make this measurement vulnerable to even very small background rates. These rates imply that not much more than one additional false event per kiloton LAr per century can be tolerated and still allow for meaningful relic SN neutrino sensitivity.

The sensitivity of LAr to relic neutrinos is addressed in some detail in the PWG document (arXiv: 1110.6249). High exposure LAr data, ideally at a relatively shallow depth to allow study of rare cosmic ray-related processes, would therefore be necessary to properly evaluate if relic SN neutrino observations will be practical in liquid argon.

SECTION 4: **Agenda of the Oral Presentations and Links to talks.**

Science Capabilities Review

Thursday 03 November 2011

Introduction - CDF Big Room in Bldg 327 (08:15-11:25)

time	[id] title	presenter
08:15	[1] Closed Executive Session (00h45')	
09:00	[15] Welcome and Opening Remarks (00h15')	WARK, David
09:15	[16] Review Goals and Organization (00h15')	SVOBODA, Robert
09:30	[17] Overview of LBNE Experiment (00h50')	Dr. DIWAN, Milind
10:20	Break (00h20')	
10:40	[18] Liquid Argon Detector (LAD) Overview (00h45')	BALLER, Bruce URHEIM, Jon

LAD Physics Associated with a Neutrino Beam - CDF Big Room in Bldg 327 (11:25-14:15)

time	[id] title	presenter
11:25	[19] Signal Efficiencies, Backgrounds, Resolutions : Analysis Tools (00h30')	Dr. REBEL, Brian
11:55	[20] Signal Efficiencies, Backgrounds, Resolutions : Performance Inputs from Operating Detectors (00h35')	CAVANNA, Flavio
12:30	Closed Committee working lunch (01h00')	
13:30	[21] Sensitivity Analysis for MH and CPV : Sensitivity Studies (00h25')	Dr. ZELLER, Sam
13:55	[22] Sensitivity Analysis for MH and CPV : Validating & Updating Sensitivity Input Assumptions (00h20')	RAAF, Jennifer

LAD Proton Decay and Astrophysics - CDF Big Room in Bldg 327 (14:15-16:30)

time	[id] title	presenter
14:15	[23] Proton Decay Detector Performance (00h25')	URHEIM, Jon
14:40	[24] Proton Decay Backgrounds (00h25')	CHURCH, Eric
15:05	[25] Supernova Detector Performance (00h25')	SCHOLBERG, Kate MUFSON, Stuart
15:30	Break (00h20')	
15:50	[26] Other Physics Measurements and Summary (00h40')	FLEMING, Bonnie

Closed Executive Session - Wilson Hall 8X - Hornet's Nest (16:30-18:30)

Friday 04 November 2011

Introduction - CDF Big Room in Bldg 327 (08:15-09:15)

time	[id] title	presenter
08:15	[8] Closed Executive Session (00h30')	
08:45	[27] Water Cherenkov Detector (WCD) Overview (00h30')	KLEIN, Joshua

WCD Physics Associated with a Neutrino Beam - CDF Big Room in Bldg 327 (09:15-11:40)

time	[id] title	presenter
09:15	[28] Signal Efficiencies, Backgrounds, Resolutions : Validation of the WC Detector Simulation (00h30')	WALTER, Chris SCHOLBERG, Kate KEARNS, Ed
09:45	[29] Signal Efficiencies, Backgrounds, Resolutions : Extraction of Signal Backgrounds and Efficiencies From SK (00h30')	KEARNS, Ed
10:15	[30] Signal Efficiencies, Backgrounds, Resolutions : Scanning Results (00h20')	MISHRA, Sanjib
10:35	Break (00h20')	
10:55	[37] Near Detector (00h15')	Prof. MISHRA, Sanjib
11:10	[31] Sensitivity for MH and CPV (00h30')	BISHAI, Mary

WCD Proton Decay and Astrophysics - CDF Big Room in Bldg 327 (11:40-15:40)

time	[id] title	presenter
11:40	[32] Proton Decay Detector Performance (00h30')	KEARNS, Ed
12:10	Closed Committee Working Lunch (01h00')	
12:40	[38] Near Detector Complex (00h30')	MAUGER, Christopher
13:10	[33] Supernova Detector Performance (00h30')	SCHOLBERG, Kate
13:40	[34] Other Physics Measurements (00h25')	KLEIN, Joshua
14:05	[35] Possible Upgrades (00h30')	KADEL, Richard
14:35	Break (00h25')	
15:00	[36] Physics Working Group Summary and Plans (00h40')	WILSON, Robert

Closed Executive Session - Wilson Hall 8X - Hornet's Nest (15:40-17:40)

Saturday 05 November 2011

Closed Executive Session - Wilson Hall 8X - Hornet's Nest (08:30-14:30)